

# EXPERIMENTAL INVESTIGATION OF BEARING CAPACITY OF CIRCULAR AND RING FOOTINGS ON GEOGRID-REINFORCED COHESIONLESS SOILS

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## Abstract

This experimental investigation describes an extensive series of reduced laboratory scale tests, conducted on circular and ring footing models rested on a geogrid reinforced cohesionless soil. The study examined the impact of several factors at different relative sand densities, such as the inner to the outer diameter ratio of the ring footing, the number of geogrid reinforcements, the depth of the initial reinforcement, and the vertical spacing between the geogrids, as well as the geogrid stiffness. The results indicated that the optimum diameter ratio of ring footings resting on loose or medium-dense cohesionless soil is 0.40 at which the maximum bearing capacity is reached, leading in a cost-effective design of the footings, while for the dense soil, a diameter ratio of 0.45 is the optimal ratio. Also, the results indicated that the optimum number of reinforcement layers which after the bearing capacity improvement can be considered negligible is three layers for the circular footing and four layers for the ring footing model. To achieve the maximum increase in bearing capacity, the study identifies optimal values for the depth of the first geogrid reinforcement layer and the vertical spacing between reinforcements, which apply to circular and ring footing. While the stiffness of the reinforcement has a significant effect on the bearing capacity, this effect is not proportional.

## Keywords:

Bearing capacity;  
Circular and ring footing;  
Geogrid;  
Reinforced sand.

## 1 Introduction

Geosynthetic materials, such as geotextiles, geogrids, geonets, geomembranes, and galvanized steel strips, have been increasingly utilized in various geotechnical engineering applications. These applications include stabilizing the earth, enhancing the maximum load-bearing capacity of foundations, and minimizing settlements in shallow footings (e.g., Reymond [1]; Zhou and Wen [2]; Tanyu et al. [3]). After the pioneering work of the French architect Henri Vidal in the mid of 1960s, soil reinforcement usage became popular in various geotechnical engineering applications. Numerous numerical and experimental studies have been performed for investigating the effect of the reinforcements on bearing capacity and settlement of shallow footings (e.g., Binquet and Lee [4, 5]; Akinmusuru and Akinbolade [6]; Fragaszy and Lawton [7]; Guido et al. [8]; Khing et al. [9]; Omar et al. [10]; Das and Omar [11]; Yetimoglu et al. [12]; Adams and Collin [13]; Otani et al. [14]; Hwang and Hong [15]; Hataf and Rahimi [16]; Michalowski [17]; El-Sawwaf [18]; Al-Sumaiday [19]; Zhou and Wen [2]; Tanyu et al. [3]; Chakraborty and Kumar [20]; Al-Jenzawi and Al-Azzawi [21]). In almost all of these studies, the depth of the first reinforcement layer ( $u$ ), the vertical spacing between layers ( $h$ ), the number of reinforcement layers ( $n$ ), and the footing shape have been studied and their effects on bearing capacity and settlement were investigated. To assess the improvement in bearing capacity, a non-dimensional value is often used, known as bearing capacity ratio BCR, which is the ratio of bearing capacity of reinforced soil to non-reinforced soil. The majority of these studies have focused on soil reinforcements under strip or rectangular footings, notwithstanding, the circular and ring footings which are appropriate for a range of constructions (e.g., transmission towers, chimneys, silos, storage tanks, spaceport bases, offshore structures, and telecommunication towers) have merely been investigated.

In the last two decades, several studies have been published to investigate the circular and ring footings behavior on reinforced soils (Boushehrian and Hataf [22]; Dash et al. [23]; Sitharam et al. [24];

Sireesh et al. [25]; El-Sawwaf and Nazir [26]; Demir et al. [27]; Chakraborty and Kumar [20]; Tafreshi et al. [28]; Sharma and Kumar [29]; Hosamo et al. [30]; Ameer and A'amal [31]; Jawad et al. [32]; Helis et al. [33]). Boushehrian and Hataf [22] conducted experimental and numerical studies to examine the impact of the initial layer's depth of reinforcement, vertical spacing, and number of reinforcement layers on the bearing capacity of circular and ring footings. The footings had an outer diameter of 150 mm and were reinforced with biaxial geogrid in sand. The soil beds were prepared in a cylindrical tank measuring 1000 mm in diameter and 1000 mm in height. The model of the ring footing had an outer diameter of 150 mm and an inner diameter of 60 mm. The researchers reported the ideal depths of the initial reinforcing layer are 1.0 and 1.2 times of the outer diameter of the circular and ring footings respectively, in addition to that, using greater than four reinforcement layers has a negligible bearing capacity improvement. Also, based on the numerical analyses, the researchers concluded that the most favourable proportion between the inner and outer diameters of the ring footing is 0.4. Boushehrian and Hataf [22] reported that increasing of the reinforcement layers leads to the decrease of the optimum vertical spacing between the layers. In their study, Dash et al. [23] examined the performance of circular footings placed on geocell-reinforced sand above soft clay. Sitharam et al. [24] conducted a series of laboratory stress tests on a circular footing model placed on reinforced soft clay. The potential benefits of the geocell reinforcement, in addition to the effect of depth, width, and height of geocell layer were presented. Sireesh et al. [25] investigated the bearing capacity of circular footing on geocell reinforced sand mattress in a cohesive bed with void. El-Sawwaf and Nazir [26] conducted a series of experimental experiments on a model of a ring foundation loaded off-centre to examine the possible advantages of reinforcing a replacement layer of sand using geogrid reinforcement, the effect of the depth of the replaced sand layer and the flexibility of the reinforcement were also investigated. The soil beds were prepared in a test box of 1000 X 1000 mm in plan and 700 mm in depth. The ring footings are modelled with a fixed outer diameter of 120 mm and varied inner diameters were used in their work. They reported that the recommended ratio of inner to outer diameters of the ring footing is 0.39, the optimum number of reinforcement layers is only three layers, also, the effective depth of the reinforced zone under the ring footing is 1.5 times of the outer diameter. Demir et al. [27] have performed eight field tests, along with numerical analyses by using finite element package PLAXIS 3D to investigate the bearing capacity of circular footing on geogrid-reinforced compacted granular fill layer overlying on natural clay deposit. Chakraborty and Kumar [20] used the upper bound theorem of the limit analysis in conjunction with finite elements and linear optimization to investigate the bearing capacity of a circular footing rested over reinforced soil with horizontal layers of circular reinforcement sheets, three distinct soil media have undergone testing: granular, cohesive frictional, and entirely cohesive. The enhancement in the maximum load-bearing capacity was demonstrated by utilizing efficiency factors multiplied by the conventional load-bearing capacity factors. They revealed that including the reinforcement results in a substantial enhancement in the footing's performance when the soil is reinforced with two layers of reinforcement sheets. Tafreshi et al. [28] conducted a set of experimental studies to evaluate the effectiveness of circular footings on sands that were reinforced with multiple layers of geocell compared to the same soil reinforced with multi-layered planar geotextile reinforcement. Sharma and Kumar [29] used finite element package PLAXIS 3D to investigate the behavior of ring footing resting on compacted randomly distributed fiber-reinforced sand under eccentric-inclined loading. Hosamo et al. [30] carried out a numerical analysis to investigate bearing capacity of a ring footing on geogrid reinforced sand, the effects of the inner to outer diameter of ring footing and the depth of the reinforcement layer were studied. The results showed that the optimum ratio of inner to outer diameter of ring footing is 0.6. Also, for a single reinforcement layer, the optimum depth of reinforcement implementation was found to be between 0.40-0.45 to increase the bearing capacity up to 20%, while for a double reinforcement layers it was 0.34-0.41 to improve the bearing capacity up to 30%. Recently, Ameer and A'amal [31] conducted a series of experimentally tests on ring footings rest on geogrid reinforced sand subjected to an inclined load. The study presented that the optimum spacing between the geogrid layers is 50% of the footing diameter and the optimum geogrid reinforcement layers is found to be 4 to reduce the lateral displacement under inclined load. In 2023, Jawad et al. [32] studied experimentally the behaviour of the ring footings on loose cohesionless soils reinforced by geogrid. They concluded that the optimum diameter ratio is 0.25, and the optimum depth of the topmost reinforcement layer as well as the optimum vertical depth between layers are around 0.25 times of the footing diameter at which the maximum improvement in bearing capacity is achieved. Helis et al. [33] used finite element analysis to investigate the bearing capacity of a circular footing on sand bed reinforced by two different reinforcement systems, geogrid and grid anchor. The optimum length of the reinforcement was determined to be 5 times of the footing diameter for both geogrid and grid anchor systems, and the optimal depth of the first

reinforcement layer is determined as 0.42 times of the footing diameter at which the highest performance of the footing capacity is reached.

While the authors cited above have made contributions to our understanding of how circular and ring footings behave on soils that are reinforced, there is currently a shortage of research on the bearing capacity of circular and ring footings on cohesionless media that are reinforced by geogrid. In many situations, the footings are required to be constructed on weak cohesionless soils, which has a low resistance and high displacement under loading. For such case, the traditional technique to improve the bearing capacity and minimize the settlement is removing part of the weak soil to be replaced by layers of base and subbase with deep and shallow compaction. Occasionally, such a technique leads to an excessive cost. Therefore, one of the most cost-effective solutions for the problem is adopting the soil reinforcement technique, hence the footing size may be reduced and the required depth of removing and replacing layers is reduced. However, to the authors' knowledge, the behavior of circular and ring footings on geogrid-reinforced sand deposits at various relative densities has not been investigated. For this reason, the present paper places emphasis on the effect of the ratio of inner to outer diameter of ring footings, the optimum geometric layout of the reinforcement layers, and the effect of the reinforcement stiffness at different relative densities of the soil for both circular and ring footings. The results of an extensive series of experimental laboratory tests on ring and circular footing models on reinforced-geogrid cohesionless soil at various relative densities are presented and the main findings and conclusions are summarized.

## 2 Model tests

The experimental tests were carried out in a rigid steel box with plan dimensions of 1200 mm X 1200 mm, and 1000 mm in depth. All the sides were made using a 4 mm thick steel plate to accommodate the soil. In order to prevent any movement of the test box, it was supported directly on two steel columns which are braced in two horizontal steel beams. The horizontal beams were fixed in the laboratory ground using eight pins. The loading system, consists a hand-operated hydraulic jack and a proving ring, was attached to a horizontal steel beam which was supported on the two columns as shown in Fig. 1. The load was applied at a rate of 1.0 kPa per second at all tests by a loading shaft to a platform with four symmetrical legs and transferred through bearing balls to the footing models in the tests. The average settlement was measured during loading by two 0.001 mm accuracy dial gauges located on diametral opposite edges of the footing model. Furthermore, under an applied loading of 2000 kPa on the footing model, four dial gauges were attached on the four box sides to detect the deflections, which were found to be very small and have a negligible effect on the experimental test results. All the inside walls of the testing box were sanded by a sandpaper and a sand block to reduce the friction as far as possible with the soil.

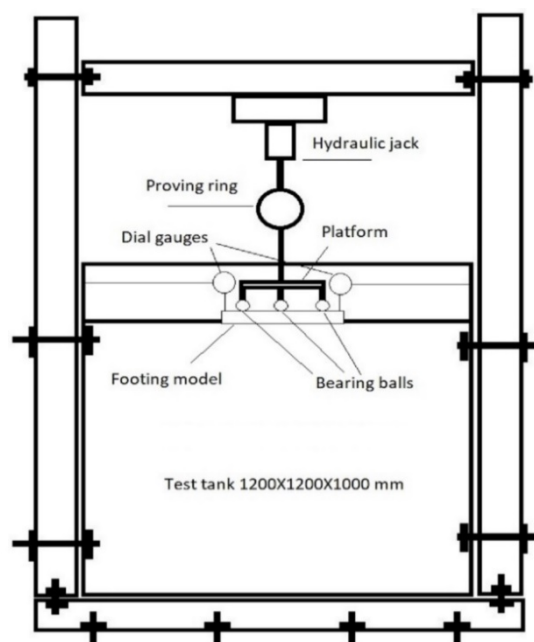


Fig. 1: Diagram illustrating the experimental equipment.

### 3 Materials used in the study

#### 3.1 Sand

The soil employed in this research is classed as poorly graded sand according to the Unified Soil Classification System (ASTM D 2478, [34]). The particle size distribution of the sand is presented in Fig. 2. The specific gravity of this sand was 2.67 according to ASTM D 854 [35]. Other characteristics of the sand are shown in Table 1.

#### 3.2 Model circular and ring footings

The circular and ring footing models were constructed using a robust steel plate with an external diameter of 150 mm and a thickness of 20 mm. The ratios of the inner to outer diameters of the footing models were 0.00, 0.20, 0.30, 0.40, 0.45, 0.50, 0.60, and 0.70. The footing models were coated with epoxy adhesive and then coated with coarse sand to create a rough surface for the experimental tests.

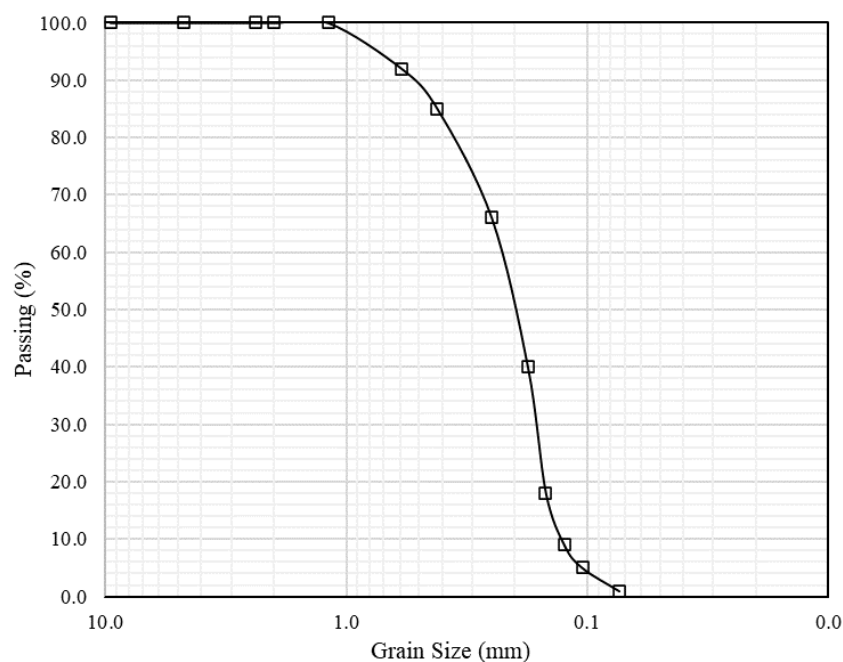


Fig. 2: Particle size distribution of the sand used in the tests.

Table 1: Properties of the sand used in the tests.

| Property                                      | Value |       |       |
|-----------------------------------------------|-------|-------|-------|
| Effective diameter, $D_{10}$ (mm)             | 0.125 |       |       |
| Coefficient of uniformity, $C_u$              | 1.76  |       |       |
| Coefficient of curvature, $C_c$               | 0.81  |       |       |
| Specific Gravity, $G_s$                       | 2.67  |       |       |
| Minimum density, ( $\text{kN/m}^3$ )          | 15.52 |       |       |
| Maximum density, ( $\text{kN/m}^3$ )          | 18.32 |       |       |
| Relative density, (%)                         | 40    | 60    | 80    |
| Dry Density, ( $\text{kN/m}^3$ )              | 16.53 | 17.08 | 17.68 |
| Residual angle of internal friction, (degree) | 34    | 38    | 42    |

#### 3.3 Geogrid reinforcement

In the current study, three types of commercially available triaxial geogrids (TX130, TX150, and TX180) manufactured from a punched polypropylene were used as a reinforcement element. The typical and technical properties of the geogrids are obtained from manufacturer's data and presented in Table 2.

Table 2: The typical and technical properties of the triaxial TX130, TX150, and TX180 geogrid.

| Properties                             | Unit              | Value |       |       | Tolerance       |
|----------------------------------------|-------------------|-------|-------|-------|-----------------|
|                                        |                   | TX130 | TX150 | TX180 |                 |
| Radial Secant Stiffness at 0.5% strain | kN/m              | 275   | 360   | 540   | -75 to -90      |
| Radial Secant Stiffness Ratio          | -                 | 0.75  | 0.80  | 0.80  | -0.15           |
| Junction Efficiency                    | %                 | 100   | 100   | 100   | -10             |
| Hexagon Pith                           | mm                | 66    | 80    | 80    | $\pm 4$         |
| Weight                                 | kg/m <sup>2</sup> | 0.18  | 0.205 | 0.315 | -0.03 to -0.035 |

#### 4 Test preparation and procedure

In both reinforced and unreinforced tests, the sand layers were created by compaction vibratory technique of soil into the testing box. In this technique, a small hand vibrator is used to apply a uniform vibration on a stiff steel plate 890 mm X 890 mm in plane dimensions for each soil layer. The time of applying the vibrator on the plate was manipulated to achieve the target relative densities of 0.40, 0.60, and 0.80, these values were chosen to represent the loose, medium-dense, and dense sand conditions in the field. The relative density achieved during the tests was measured for each soil layer by collecting samples at four different locations in the test box in small aluminium cups of known volume. However, the sand was compacted in layers of 25 mm thickness until reaching the footing level. The geogrid sheets used in each test were new.

As final steps of test preparation, after positioning the footing and loading system, the hydraulic jack was utilized to apply the load in incremental steps until the failure was reached. Throughout the test, the load increments were held at a constant value, and the settlement of the footing model was closely monitored and observed until stabilization was achieved. Figure 3 displays a schematic layout of the soil, footing model, and soil reinforcement.

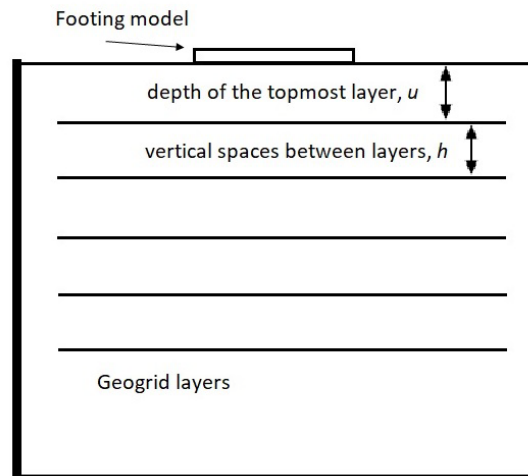


Fig. 3: A schematic layout of the soil, footing model, and soil reinforcement.

#### 5 Tests program

An extensive experimental program was carried out to study the behavior of circular and ring footings on reinforced sand at various soil relative densities. A total of eight series of tests were performed, as presented in Table 3. In the case of unreinforced sand, three series of tests (Test series 1, 2, and 3) were performed by varying the inner to outer diameter ratios of the models at three different sand relative densities (0.40, 0.60 and 0.80). Then one series of tests (Test series 4) was carried out to study the effect of the number of reinforcement layers at various sand relative densities for both circular and ring footing models. The three series (Test series 5, 6 and 7) were conducted to determine the effect of the depth of the first geogrid reinforcement layer and the vertical spacing between the geogrid layers at different sand relative densities for both circular and ring footing models. Two nondimensional variable parameters,  $u$  and  $h$ , expressed as a function of footing outer diameter ( $D_o$ ) as  $u/D_o$  and  $h/D_o$ , were used to describe the depth of the topmost (first reinforcement) layer and the vertical distance

(spacing) between the geogrid layers. The last series (Test series 8) was performed to investigate the effect of the reinforcement stiffness at different sand relative densities for both circular and ring footing models. Several tests were repeated at the same test conditions to check the accuracy of the results and the apparatus performance. The stress-strain variation was close for the repeated tests with a maximum difference around 3%, which considered to be negligible. An initial series of tests were performed to obtain the width of the reinforcement layer that provides the maximum improvement in bearing capacity, it has been found that using a reinforcement layer with a width more than four times of the outer diameter of the footing has no further significant improvement on bearing capacity. Therefore; the width of the reinforcement layers has been kept constant as four times of the outer diameter of the footing model for both circular and ring footing cases for the entire testing program.

Table 3: Tests program.

| Series | Constant parameters                       | Variable parameters                                                                                                          |
|--------|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| 1      | $R_d=40\%$                                | $D_i/D_o = 0.0, 0.20, 0.30, 0.40, 0.45, 0.50, 0.60, 0.70$                                                                    |
| 2      | $R_d=60\%$                                |                                                                                                                              |
| 3      | $R_d=80\%$                                |                                                                                                                              |
| 4      | $u/D_o = 0.30, h/D_o = 0.30$              | $N = 1, 2, 3, 4, 5$<br>$R_d = 40\%, R_d = 60\%, R_d = 80\%$<br>$D_i/D_o = 0.0, 0.40 / 0.45$                                  |
| 5      | $R_d = 40\%$<br>$N = 3$<br>$u/D_o = 0.30$ | $h/D_o = 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50$                                                                           |
|        | $R_d = 40\%$<br>$N = 3$<br>$h/D_o = 0.30$ | $u/D_o = 0.20, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55$                                                                           |
| 6      | $R_d = 60\%$<br>$N = 3$<br>$u/D_o = 0.30$ | $h/D_o = 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50$                                                                           |
|        | $R_d = 60\%$<br>$N = 3$<br>$h/D_o = 0.30$ | $u/D_o = 0.20, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55$                                                                           |
| 7      | $R_d = 80\%$<br>$N = 3$<br>$u/D_o = 0.30$ | $h/D_o = 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50$                                                                           |
|        | $R_d = 80\%$<br>$N = 3$<br>$h/D_o = 0.30$ | $u/D_o = 0.20, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55$                                                                           |
| 8      | $u/D_o = 0.30, h/D_o = 0.30$              | $D_i/D_o = 0.0, 0.40 \text{ or } 0.45$<br>$N = 1, 2, 3, 4, 5$<br>$R_d = 40\%, R_d = 60\%, R_d = 80\%$<br>TX130, TX150, TX180 |

## 6 Results and discussion

A total of 140 tests were carried out on circular and ring footing models resting on geogrid reinforced and unreinforced sand deposits. The load-settlement curve was plotted for all the tests, and the ultimate bearing capacity was determined using the tangent technique. This technique involves drawing two tangents, one from the initial portion and one from the final portion of the curve. The load corresponding to the intersection point of these two tangents is considered as the ultimate bearing capacity of the footing. As in the literature, a non-dimensional value known as bearing capacity ratio BCR, which is the ratio of bearing capacity of reinforced soil to non-reinforced soil, is used to represent the improvement in bearing capacity due to reinforcement inclusions. The reference case for all the results represented in this work was the non-reinforced case for the circular model on a sand deposit of a relative density of 40%.

### 6.1 Determination of the optimum diameter ratio

Twenty-four tests in three series were performed to determine the optimum value of inner to outer diameter ratio of the ring footing at different sand relative densities. Figure 4 shows the variation of pressure with settlement of the circular footing model for unreinforced sand deposits at relative densities of 0.40, 0.60, and 0.80. The behavior illustrated in Fig. 4 shows the improvement of the initial stiffness and the bearing pressure at the same settlement level when relative density of the sand increases. For

example, at a settlement level of 10 mm, the bearing pressure of the circular footing increased 3.35 and 4.95 times for the medium-dense and dense sand conditions relative to the condition of loose sand.

Figure 5 displays the typical variation in bearing pressure as circular and ring footings settle on dense sand without reinforcement. In this series, the relative density of the sand deposit was kept constant as 80%, except that the ratio of the inner to outer diameter of the footing models was varied as (0.0, 0.20, 0.30, 0.40, 0.45, 0.50, 0.60, and 0.70). Figure 5 shows that the bearing pressure as well as the settlement are improved when inner to outer diameter increases until reaching the maximum improvement at a ratio of 0.45, then after, the bearing pressure decreases until being close to that obtained from the circular footing model at a diameter ratio of 0.60.

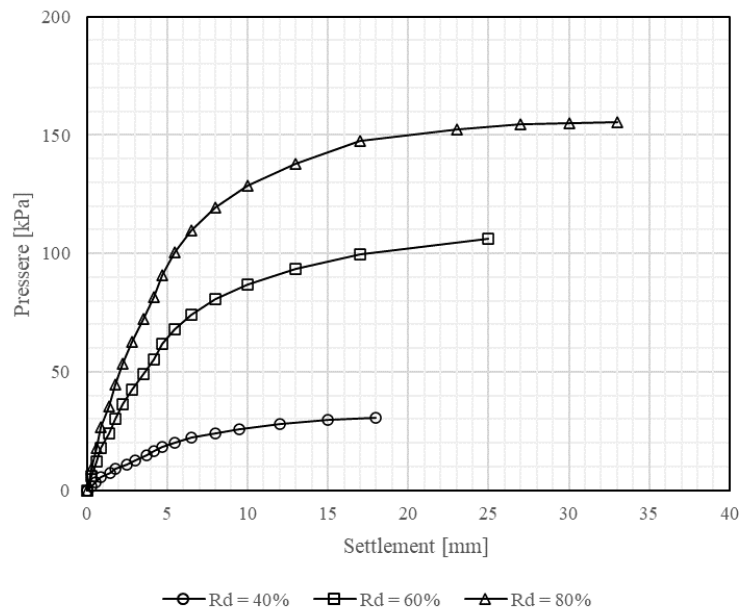


Fig. 4: Variation of pressure with settlement of circular footings at various sand relative densities.

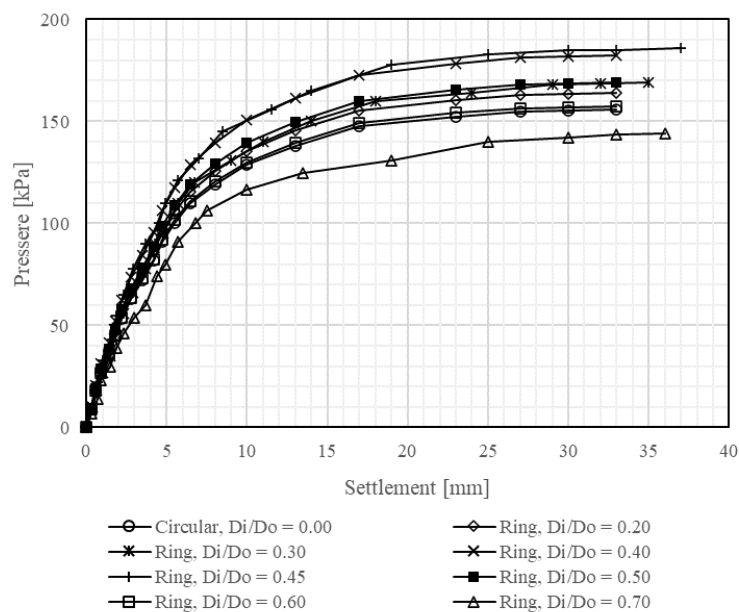


Fig. 5: Variation of pressure with settlement for circular and ring footings on dense sand.

However, the bearing capacity ratio BCR is plotted versus the ratio of the inner diameter to the outer diameter ( $D_i/D_o$ ) in Fig. 6, for the loose, medium dense, and dense sand conditions. Figure 6 clearly indicates that the maximum bearing capacity improvement, which is represented as a solid series Limit A, can be obtained at a diameter ratio of 0.45 for the dense sand deposit and 0.40 for both loose

and medium-dense sand deposits. The bearing capacity improvement was 5.6 times for the ring footing with a diameter ratio of 0.45 resting on dense sand relative to a circular footing resting on loose deposit, while, it was 3.7 and 1.2 times for the ring footing with a diameter ratio of 0.40 resting on medium-dense and loose sand respectively. This finding is in a good agreement with the results reported by El-Sawwaf and Nazir [26], and Boushehrian and Hataf [22], who reported that the maximum improvement obtained from ring footing can be reached at diameter ratios of 0.39, and 0.38 respectively. Also, Fig. 6 illustrates that the original value of the bearing pressure of a circular footing can be obtained by a ring footing at diameter ratios 0.45, 0.48, and 0.6 for the loose, medium dense, and dense sand deposits respectively, as represented in the dashed series Limit B. In simple words, the same bearing capacity of a circular footing on dense sand can be achieved by a ring footing with a diameter ratio of 0.6, resulting in a cost-effective design.

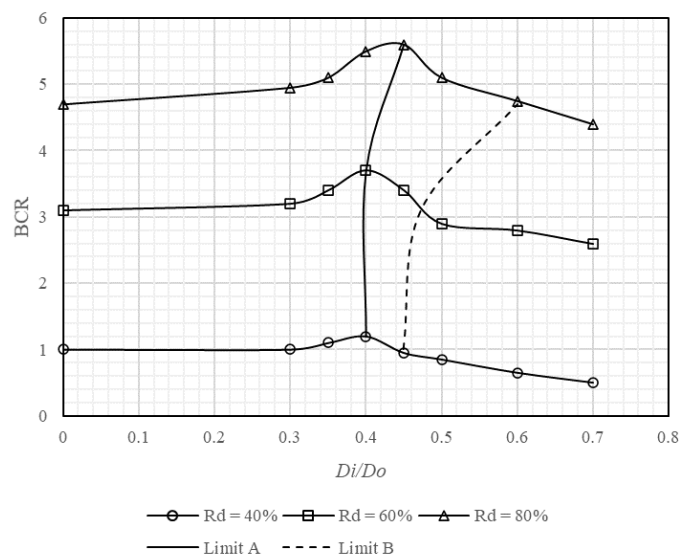


Fig. 6: Variation of BCR with  $D_i/D_o$  at different sand relative densities without any reinforcement.

## 6.2 Determination of the optimum number of the reinforcement layers

Thirty tests were conducted to investigate the effect of number of the geogrid reinforcement layers for both circular and ring footing models on sand deposit at relative densities of 0.40, 0.60, and 0.80. Determination of an optimum number of the geogrid layers is not a simple task since it is relating to the depth of the influence effect under the model and very dependent on the depth of the topmost layer and the distances between the layers. However, the topmost layer depth and the distance between the geogrid layers  $u$  and  $h$  were kept constant through the tests to minimize their effect on the results in this Series as 30% of the outer diameter of the footing model. The optimum inner to outer diameter ratio ( $D_i/D_o$ ) for the ring footings corresponding to the sand deposit relative density as presented in the previous section was adopted in this test Series.

The results of the tests are presented in Fig. 7 which presents BCR variation against the number of reinforcement layers for circular and ring footing models on sand deposit at different relative densities. In general, for all cases, the improvement in BCR is evident when inclusion more geogrid layers. However, for circular footing models, the improvement can be considered as negligible when more than three reinforcement layers are used, then the rate of increase in BCR tends to be constant. For example, using four reinforcement layers may improve the BCR only 1.5% than using three layers for the dense sand deposit. This finding is in a good agreement with the results stated by El-Sawwaf and Nazir [26], El-Sawwaf [18], and Das et al. [36] who reported that the optimum number of reinforcement layers is three. For the ring footing models, the improvement of BCR continuous after using more than three layers, especially for the loose sand deposit. For example, using five reinforcement layers under ring footing model increases the BCR for the loose sand 16.67% than that obtained from using three layers. However, for the dense and medium dense sands, the improvement in BCR increases 3.75 and 7.27 % respectively when five layers are used instead of three reinforcement layers. The same finding is concluded by Boushehrian and Hataf [22] who reported that the improvement on BCR can be considered negligible when more than four reinforcement layers are used.

### 6.3 Determination of the optimum values of $u/D_o$ and $h/D_o$ ratios

As mentioned before, for determining the optimum values of the depth of the topmost layer and the vertical spacing between the geogrid layers, two nondimensional variable parameters,  $u$  and  $h$ , expressed as a function of footing outer diameter ( $D_o$ ) as  $u/D_o$  and  $h/D_o$ , were used. The three series (Test series 5, 6 and 7) were conducted for that goal. Determination of an optimum values of  $u/D_o$  and  $h/D_o$  is a significant challenge since it is dependent on the depth of the influence effect under the model and very relating to the number of geogrid layers. However, the number of the reinforcement layers were kept constant through the tests to minimize their effect on the results in Series 5, 6 and 7 as four layers. Also, the inner to outer diameter ratio ( $D_i/D_o$ ) for the ring footings corresponding to the sand deposit relative density were adopted in these test Series as the optimum values presented previously. However, for both circular and ring footing models on sand deposit at relative densities of 0.40, 0.60, and 0.80, the depth of the topmost geogrid layer have been altered and the bearing capacity was assessed for each case. The vertical spaces between the geogrid layers were kept as 30% of the outer footing diameter as in the previous section to minimize its effect on the results as possible.

The results reveal that the optimum value of  $u/D_o$  is not a unique value and it depends in the first place on the relative density of the sand deposit. As it can be noticed from Fig. 8, which represents the relationship between the BCR and the  $u/D_o$ , the bearing capacity ratio BCR initially slightly increases as  $u/D_o$  increases up to reach its maximum improvement for both circular and ring footing models at 0.30, 0.40, and 0.45 for relative densities of 0.40, 0.60, and 0.80 respectively. Thereafter, the BCR decreases with further increase in  $u/D_o$ .

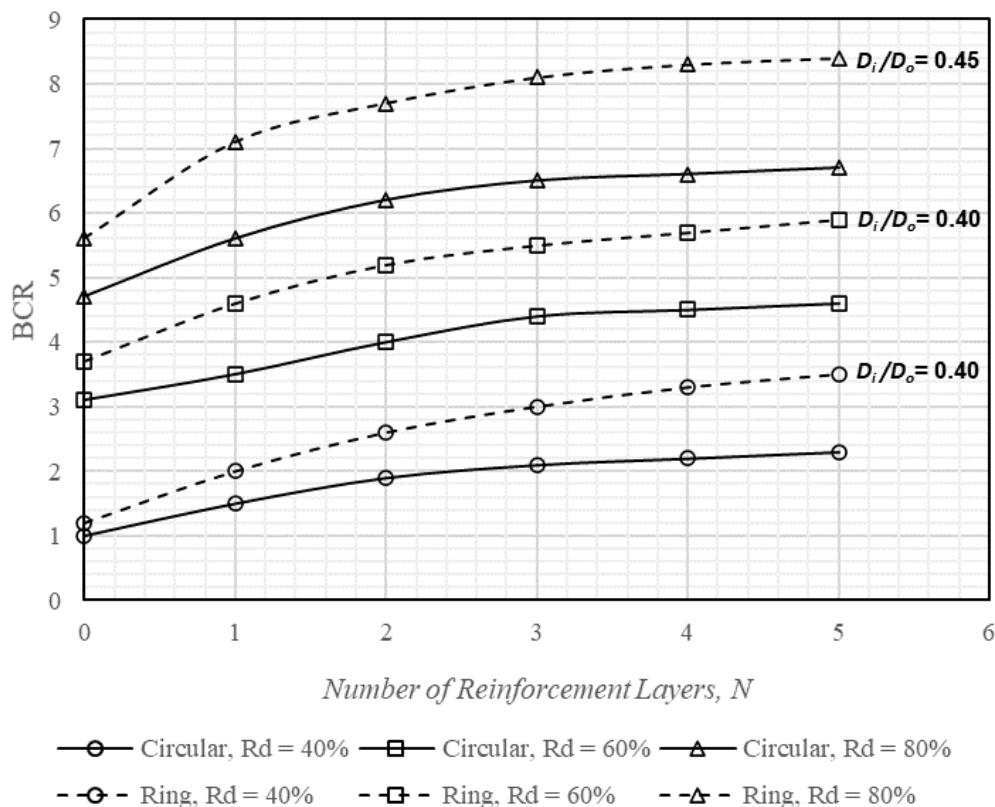


Fig. 7: Variation of BCR with  $N$  for circular and ring footings at varying sand relative densities, [ $u/D_o = 0.30$ ,  $h/D_o = 0.30$ ].

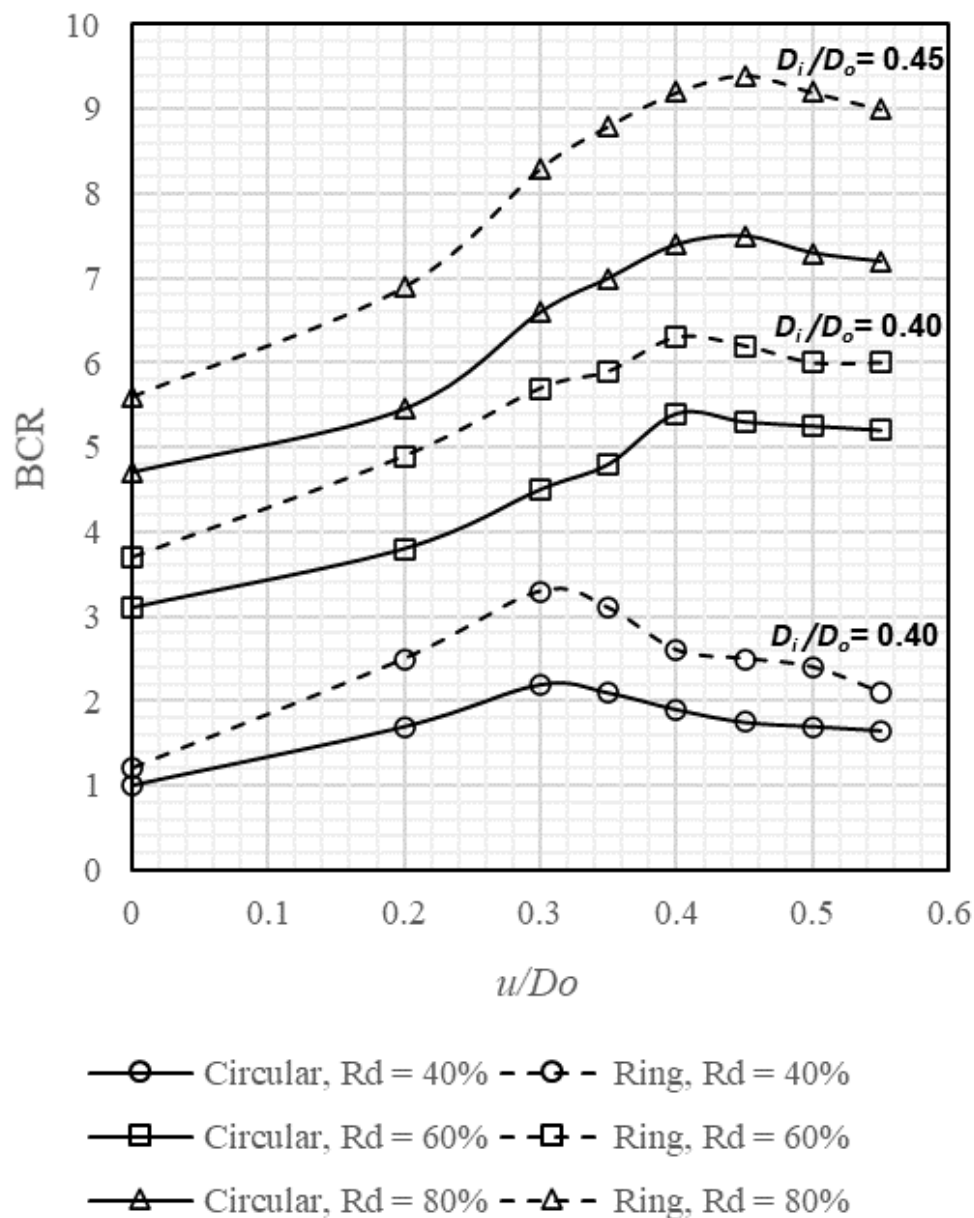


Fig. 8: Variation of BCR with  $u/D_o$  for circular and ring footings at varying sand relative densities,  $[N = 4, h/D_o = 0.30]$ .

The same methodology is employed to ascertain the optimal values of  $h/D_o$  for circular and ring footing models. The vertical spacing between the geogrid layers is altered, and the bearing capacity of the footings is established in each instance. Also, for the same purpose mentioned above, the depth of the topmost geogrid layer was kept as 30% of the outer footing diameter. The results are presented in Fig. 9, which establishes the relationship between the BCR and the  $h/D_o$  for both ring and circular footing models at varied relative density cases. As is apparent from Fig. 9, for the ring and the circular footing models, the optimum value of  $h/D_o$  relies on the sand's relative density and furthermore on the footing model itself. The maximum improvement in BCR for the ring footing models occurs at  $h/D_o$  values of (0.20, 0.25, and 0.30) for loose, medium-dense and dense sand respectively. These values tend to be slightly higher for the circular footing model and are typically (0.25, 0.30, and 0.35) for loose, medium-dense, and dense sand deposits. However, if the vertical space between reinforcement layers is increased beyond these values, it can result in a reduction of the BCR.

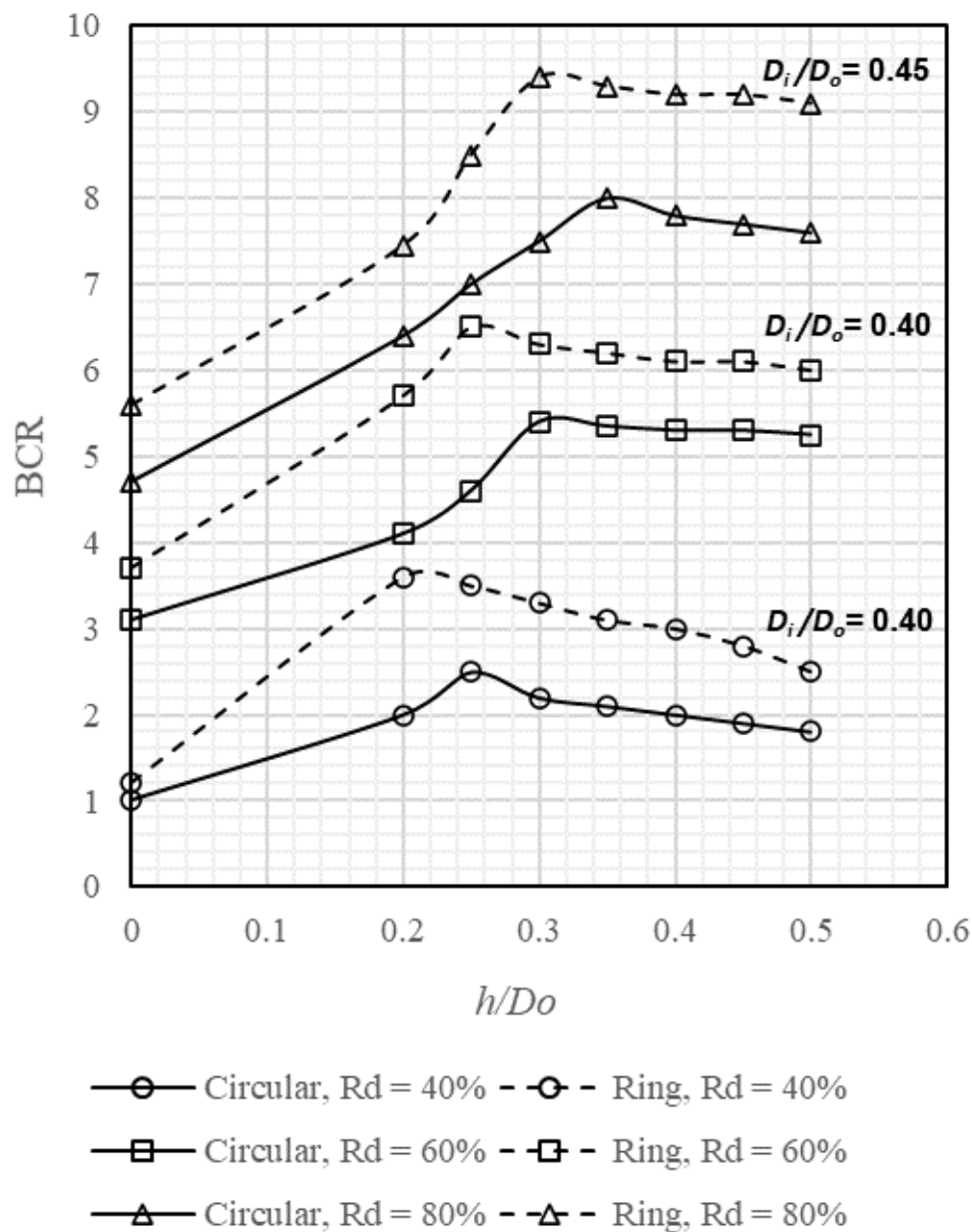


Fig. 9: Variation of BCR with  $h/D_o$  for circular and ring footings at different sand relative densities, [ $N = 4$ ,  $u/D_o = 0.30$ ].

#### 6.4 Effect of geogrid reinforcement stiffness

To investigate the effect of the geogrid reinforcement stiffness at different sand relative densities for both circular and ring footing models, some of the tests were repeated at the same conditions with using triaxial TX150 and TX180 geogrid instead of triaxial TX130. The TX180 and TX150 geogrid have 1.31- and 1.96-times stiffness of that offered by TX130 respectively. The characteristic and technical attributes of the triaxial TX150 and TX180 geogrids are derived from the data provided by the manufacturer and displayed previously in Table 2.

The other geometry parameters of the reinforcement were kept constant as 0.30 ( $u/D$  and  $h/D$ ). For the all three types of geogrid, the BCR values were plotted against the number of reinforcement layers for circular and ring footing models at medium dense and dense sand deposits (Relative densities 60 and 80%) as shown in Figs.10 and 11. As it can be seen in Figs. 10 and 11, inclusion of a stiffer geogrid results in an increase of BCR for both medium and dense sand deposits for both circular and ring footing models. Both figures show clearly that the improvement in bearing capacity for the medium sand deposits is slightly higher than that obtained from the dense sand deposit.

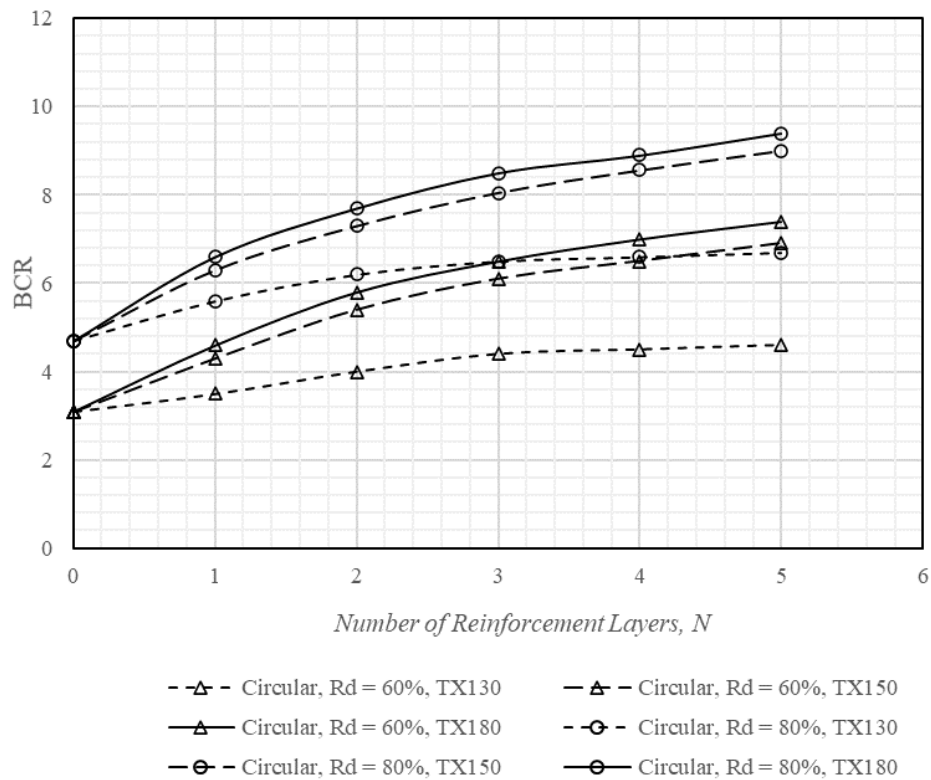


Fig. 10: Variation of BCR with  $N$  for circular footings at various relative densities and geogrid,  $[u/D_o = 0.30, h/D_o = 0.30]$ .

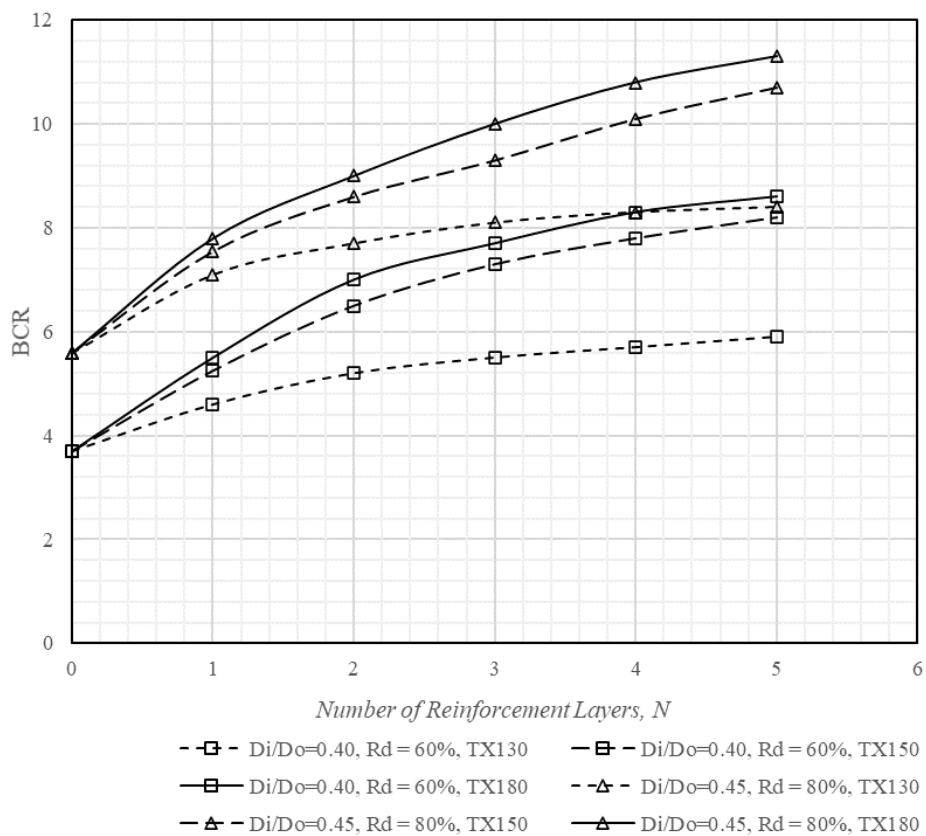


Fig. 11: Variation of BCR with  $N$  for ring footings at various relative densities and geogrid,  $[u/D_o = 0.30, h/D_o = 0.30]$ .

For example, regarding the circular footing model, inclusion four layers of TX180 geogrid in the medium dense sand leads to increase BCR 56% than that obtained from using the same number of TX130 geogrid layers, while the BCR increases 35% for the dense sand deposit when TX180 geogrid is used instead of TX130. The same behaviour occurs for the ring footing model, whereas BCR increased 46% and 31% when TX180 is used instead of TX130 for the medium dense and the dense sand deposits respectively regarding a diameter ratio of 0.40 for medium-dense and 0.45 for the dense soil. A similar pattern is observed when TX150 is used, the use of four layers of TX150 geogrid in medium dense sand, in comparison to using the same number of TX130 geogrid layers, results in a 44% and 37% increase in the BCR for the circular and ring footing models respectively. Similarly, when TX150 geogrid is used instead of TX130 in a dense sand deposit, the BCR increases by 30% and 21%. However, the increase in bearing capacity shows a modest tendency to remain constant beyond the fourth or fifth layer of geogrid reinforcement.

An important point to note is the comparison of BCR improvement between using TX180 geogrid and TX150 geogrid. It is noteworthy that although TX180 geogrid has a stiffness that is 1.5 times that of TX150 geogrid, the resulting BCR improvement obtained of using TX180 was between 5% and 12% than that from using TX150, meaning that the improvement in BCR is not directly proportioned with the geogrid reinforcement stiffness. A similar trend was reported in Boushehrian and Hataf [22] theoretical study on the tensile rigidity of reinforced sand, where they found by using finite element method that selecting a more rigid reinforcement did not necessarily lead to a better BCR results. However; for the best knowledge of the authors, no experimental study has been conducted to support that conclusion.

## 7 Conclusions

The results of a comprehensive set of laboratory-scale load tests on circular and ring footings supported on geogrid-reinforced cohesionless soil have been presented and discussed in this paper. The effects of the inner to outer diameter ratio, number of reinforcement layers, depth of the topmost layer of the geogrid, the vertical spaces between layers, and the reinforcement stiffness were investigated. The tests were conducted under varying sand conditions, ranging from loose to medium-dense and dense. Based on the findings from the present investigation, the following main key conclusions are made and given below.

1) The maximum improvement in both bearing capacity and settlement for ring footing is achieved at a diameter ratio of 0.45 for the dense sand condition and 0.40 for medium dense and loose sand state. Beyond these ratios, the bearing capacity decreases until it reaches the same value obtained from the same diameter circular footing at diameter ratios of 0.60, 0.48, and 0.45 for the dense, medium-dense, and loose sand condition respectively.

2) Inclusion more geogrid layers improve the bearing capacity; however, this improvement can be considered as negligible for the circular footing model when more than three reinforcement layers are used. On the other hand, for the ring footing model, the improvement in bearing capacity continues as more reinforcement layers are added, up to five layers.

3) The optimum depth of the topmost geogrid-reinforcement layer is not a unique value. For both circular and ring footing models, the greatest bearing capacity is achieved at  $u/D_o$  of 0.30, 0.40, and 0.45 for loose, medium-dense, and dense sand accordingly.

4) The optimal vertical distances between the reinforcing layers for the ring footing model, expressed as the ratio of  $h/D_o$ , at which the maximum improvement in bearing capacity is obtained are 0.20, 0.25, and 0.30 for loose, medium-dense, and dense sand, respectively. Meanwhile, for the case of circular footing models, these values are slightly greater, specifically 0.25, 0.30, and 0.35 at sand relative densities of 40%, 60%, and 80%, respectively.

5) The inclusion of a stiffer geogrid in a medium-dense sand deposit results in an improvement of bearing capacity for both circular and ring footing models, and it is slightly higher than that obtained in the dense sand condition. However, the bearing capacity improvement resulting from using a stiffer reinforcement is not directly proportional.

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